8.—The Tides of South-Western Australia

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An account is given of the chief characteristics of the tides at the ports of Fremantle, Geraldton, Bunbury, and Albany. The tides are mainly of daily type and of small range (maximum about 3 ft at Fremantle and 4 ft at Albany). When the declination of the moon exceeds about 10° the tides are always of daily type; but tides of semidaily type occur for several successive days in each tropic lunar cycle when the moon is near zero declination and the sun near the equinox.

Sea level varies both with atmospheric (wind and barometric pressure) and hydrologic conditions (water temperature and salinity); the extreme range of daily sea level is about 4 ft at Fremantle—greater than the maximum tidal range. Monthly sea level is generally about one foot higher in winter than in summer, but there is much variation from year to year.

Introduction

The tides of the coast of south-western Australia are in many respects unusual. They are generally daily, with only one high and one low water in each 24 hours, and with low water at about the same time on successive days, but getting gradually earlier through the year; the daily range of the tide is small, so small that meteorological and hydrological forces produce changes in sea level of the same order of magnitude. As a result long range predictions of height of tide are of little value and are therefore not published. These facts are not generally known locally and it is commonly assumed that, despite their small range, the tides behave in the same general way as on the coasts of northern Europe.

The main characteristics of the tides are of course well known to those concerned with shipping and the maintenance of port installations. Tydeman (1948) in his "Report on Port of Fremantle," states: "For the purpose of port construction and operation, Fremantle may be regarded as tideless. The range of movement of the sea is small and generally is little more than in the Mediterranean, generally referred to as tideless. The normal advantages of tides in port operation and construction cannot be employed owing to the smallness of tidal range, a disadvantage at Fremantle." Again: "Thus, unlike most ports, tides at Fremantle follow no fixed law and are irregular and unpredictable." These statements are sufficient from the point of view of the harbour authority because, as stated above, height of tide cannot be predicted with sufficient accuracy to make it worth while publishing tide tables. Nevertheless the tidal, that is the periodic, water movements do follow known laws, and both time and range of tide can be predicted with reasonable accuracy.

Curlewis (1915) described the tides at Fremantle and Port Hedland; he stressed the apparent irregularity of the Fremantle tides and the influence of the weather on them, but showed that they "depend to a large extent on the moon's declination, and from its position the range of tide may be gauged fairly accurately." He calculated harmonic constants* for both ports and records these together with others obtained previously. Bennett (1939) analysed the 1933 records and prepared graphs by means of which it is possible to "predict" height of high and low water, provided barometric pressure is known. Such predictions are generally accurate to within half a foot. He also gives a graph showing percentage time of exposure at different levels. Both accounts are incomplete in certain respects and some of the data have been misinterpreted.

The present paper is an attempt to set down succinctly what are the tidal movements on the south-west coast and what are believed to be the causes of these movements. It is based on a study of the tide records from the ports of Fremantle, Geraldton, Bunbury, and Albany for a number of years. This study was begun in an attempt to explain the discrepancies between "predicted" and actual water movements, however a much fuller analysis will be necessary before quantitative data can be given relative to the influence of weather on the tides.

Definition: "Range of tide" here means the difference in vertical height between highest and lowest water levels reached in any 24-hour period. Mean ranges have been calculated on this basis. In the use of other terms we have followed Marmer (1951), except that an arbitrary distinction has been made between tides of daily and semidaily type for the purpose of estimating the relative numbers of each (page 46).

Causes of the Tides

Tides are raised by the combined gravitational forces of the moon and sun attracting the water of the oceans. These forces set up oscillations within the various ocean basins in phase with the movements of the moon and sun relative to the rotating earth. The tidal ebb and flow at any particular place is the resultant of the position of the place in the oscillating system, the physiography of the ocean floor, the shape of the coastlines, and the size of the basin. These tidal water movements are modified

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* figures that define the constituents of the tides and from which it is possible to predict the tides.

locally by meteorological and hydrological forces; e.g., by the winds, which blow the water on to or away from the shore; by changes in air pressure, raising or lowering the water surface; and by variations in the density of the sea water caused by water temperature and salinity.

Full accounts of the tides and of tidal theory will be found in Marmer (1926), Doodson and Warburg (1941), or Russell and Macmillan (1952). Dates and times of occurrence of lunar and solar phenomena mentioned here will be found in the annual publication "The Nautical Almanack" (H.M. Stationery Office, London).

The gravitational tide-producing forces have periods that are approximately semidaily, daily, or half a month or more (long-period forces). At any particular place, or at a particular phase in a long-period cycle, (a) semidaily forces may be dominant and cause the tides to be of semidaily type, with two high waters and two low waters in each period of apparent revolution of the moon (24.8 hr), (b) daily forces may be dominant and cause tides of daily type with only one H.W. and one L.W. in each day (24 hr), or (c) the two components may be about equal and the tides of mixed type with two H.Ws and two L.Ws of markedly inequal height. There is no sharp distinction between these three types of tide and intermediate conditions are observed. All three types of tide are illustrated in the record shown in Fig. 1: semidaily tides on 9th to 10th March, daily tides from 28th to 31st, and mixed tides on 21st and 25th.

The following are the principal astronomic influences that determine the nature of the tides.

(i) The different periods of apparent rotation of the sun (24 hr) and moon (24.8 hr) about the earth cause the moon to appear successively: in the same direction as the sun (new moon), at 90° to it (first quarter), on the opposite side of the earth (full moon), again at 90° (last quarter), and back to new moon. This is the synodic month, with a period of approximately 29½ days.

When the moon is full or new the gravitational attractions of the two bodies supplement one another and tidal ranges of semidaily tides are increased (spring tides), at first and last quarter the attractions oppose one another and the tidal ranges are decreased (neap tides). Thus there are two maxima and two minima in each synodic cycle.

(ii) The moon revolves around the earth in an ellipse from perigee (shortest distance) through apogee (greatest distance) and back to perigee. This is the anomalistic month, with a period of approximately 27½ days.

When the moon is at perigee tidal ranges are increased, when at apogee they are decreased. There is only one maximum and one minimum in each cycle.

(iii) The plane of the moon's orbit is inclined to the plane of the earth's equator, and the moon is successively: at maximum declination north, above the earth's equator (zero declination), at its maximum declination south, above the equator, and back to maximum declination north. This is the tropic month, with a period of approximately 27⅓ days.

When the moon is at maximum north or south declination the daily component of the tide is always greater, tending to produce tides of daily type. When the moon is approaching zero declination the semidaily component is normally greatest, tending to produce tides of semidaily type. Tides occurring near maximum declination are "tropic" tides and those occurring near minimum declination are "equatorial" tides. There are two maxima and two minima in each tropic cycle, the intervals between successive equatorial tides being 12 to 15 days.

The angle of inclination of the moon's orbit to the earth's equator varies from a maximum of 28½° to a minimum of 18½°. This is the nodal cycle, with a period of 18.6 years. As a result the magnitude of the daily component also varies; this was least in 1941, increased to the maximum in 1950 and will decrease again until 1958.

(iv) The plane of the earth's orbit around the sun is similarly inclined to the plane of the earth's equator at 23½°. The sun is successively: at maximum declination south (soltice, about December 22nd), over the equator (equinox, March 21st) at maximum declination north (solstice, June 22nd), over the equator (equinox, September 23rd), and south again. Period one solar year.

At the solstices the daily component of the tides is reinforced; at the equinoxes the semidaily component is reinforced.

The effect of these and other minor modifying forces on the tides at any particular place differs with latitude and coastal topography. On the north-west coast of Australia, as in most parts of the world, the semidaily component is dominant and the tides are of semidaily type. There is a regular succession of spring and neap tides following the phases of the moon, and the range of these is augmented at the equinoxes producing the equinoctial or "king" tides.

On the coast of south-western Australia however the daily tidal component is dominant and the tides are mainly of the daily type; there is generally only one H.W. and one L.W. each day, and tides of semidaily type only persist for 3 or 4 days at a time when both the lunar and solar semidaily components are near their maximum. Tidal range is greatest near maximum lunar declination (tropic tides) and least near zero declination (equatorial tides), and the tropic tides are greater at the solstices than at the equinoxes.

Tides of the West and South Coast

Fremantle

Tidal movements are recorded by a Bailey patent tide machine situated on the southern side of Fremantle harbour and near its entrance. Continuous records have been taken since 1897. Because the harbour is in the mouth of the Swan River estuary the gauge also records river

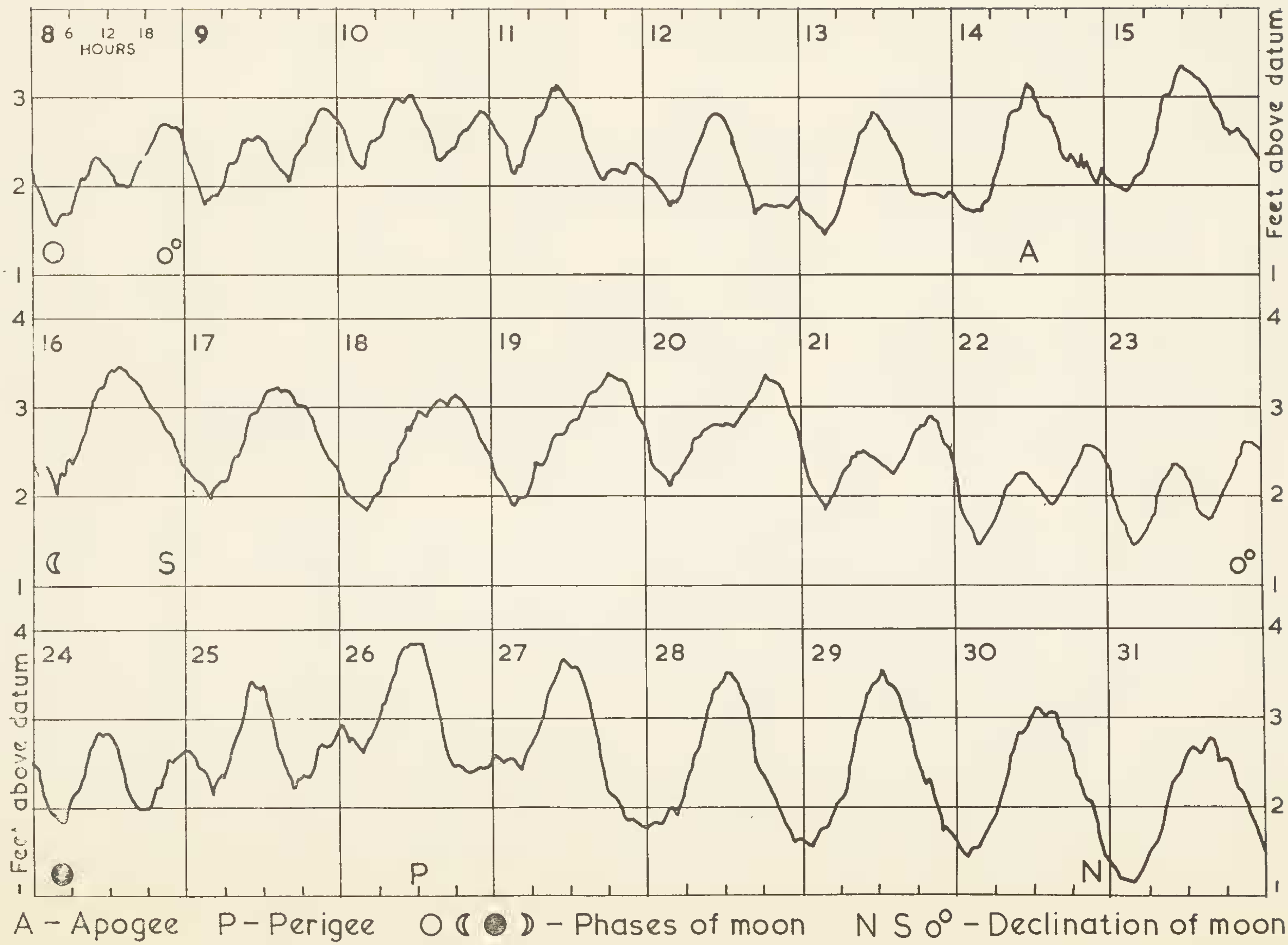

Fig. 1.—Fremantle tide record, March, 1955.

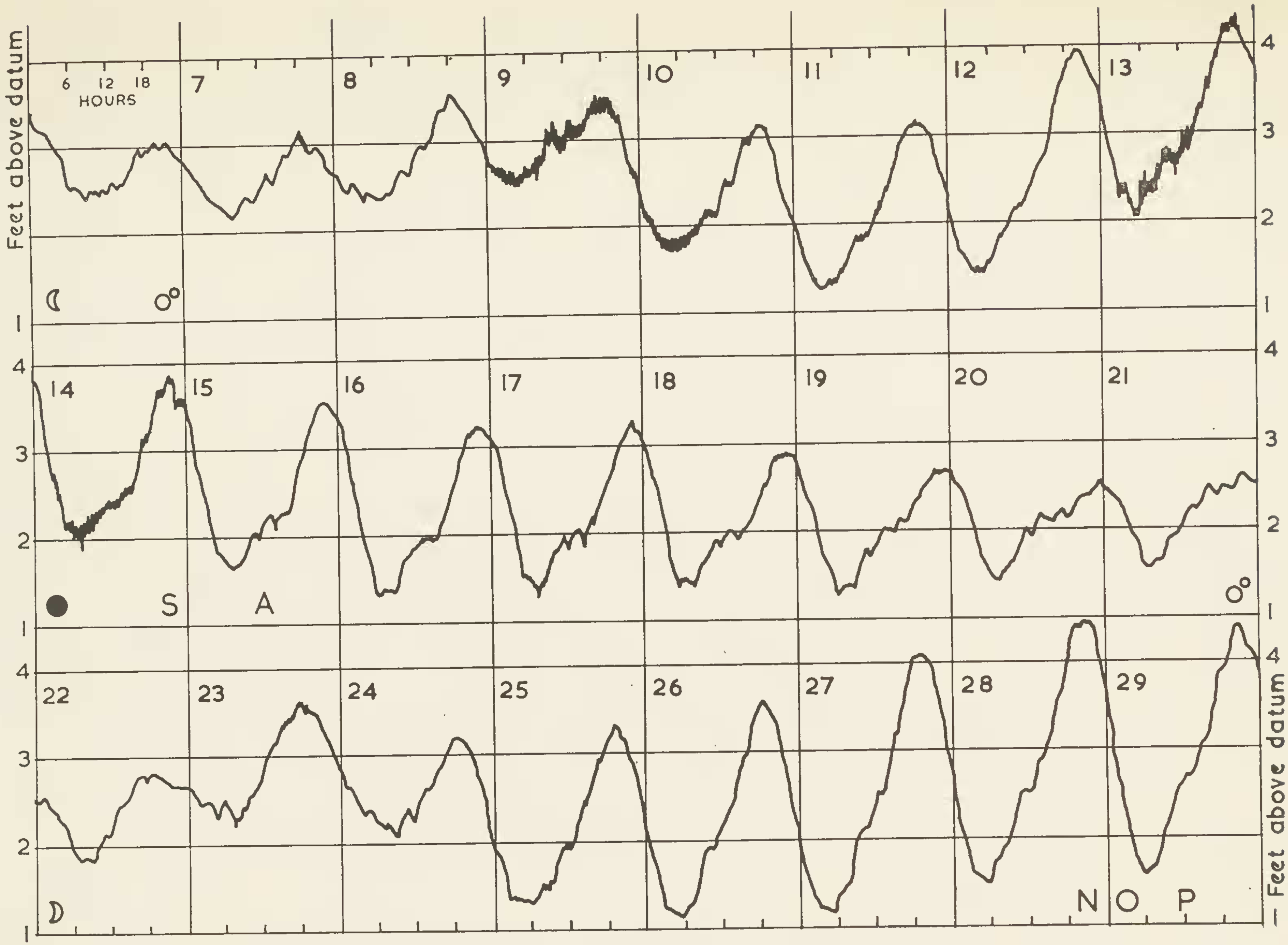

Fig. 2.—Fremantle tide record, December, 1955. For symbols see Fig. 1.

floods, but the influence of these is seldom great. Datum was fixed in 1892 by C. Y. O'Connor, then Engineer-in-Chief of the Public Works Department, at lowest low water, and levels on the gauge are relative to this; the tide very rarely reaches this level. The datum now accepted by the Australian Port Authorities Association is 0.3 ft above the gauge datum; this conforms to the definition of Indian Spring Low Water.

In preparing the following account we have given special attention to the records for the years 1913 and 1941, for which tide predictions were issued by the U.S. Coast and Geodetic Survey, and to the years 1949 to 1955.

Nature of the tide.—Typical tidal cycles, with the associated lunar phenomena, are shown in Fig. 1, from which the relation of the type to the tropic lunar cycle is evident. Tides of daily type with H.W. and L.W. about 12 hours apart occur near maximum declination, and tides of semidaily type occur near zero declination with two H.Ws and two L.Ws at about six-hour intervals. Between maximum and zero declination the tides change progressively and there are tides of mixed type, transitional in form between the typical daily and typical semidaily types. For the purpose of this investigation a somewhat arbitrary distinction has been adopted between the daily and semidaily types; a tide was regarded as semidaily if there were two high and two low waters within about 24 hours with a range exceeding 0.4 ft for a high-low sequence. This figure was adopted to avoid confusion between the smaller tides and the frequent minor oscillations which register up to 0.3 ft but seldom more. With a better damped instrument the second peak is identifiable when it has an amplitude of only 0.1 ft.

The number of days with tides of semidaily type in each tropic cycle varies with the declination of the sun. At the equinoxes there are from 4 to 7 each time the moon is near zero declination (13 to 15 in a calendar month); at the solstices there are usually none, and at zero lunar declination tides of daily type persist (Fig. 2). The mixed tides, whether at the solstices or at other times of the year, show vanishing tides; the water level stands for up to 12 hours near high or low water, and sometimes at intermediate levels (Fig. 1, March 12-13 and 26-27, Fig. 2, Dec. 21-22).

Range of tide.—The observed range of the tide also varies with the tropic lunar cycle; it is greatest at the tropic tides and least at the equatorial tides. The range in any one day seldom exceeds 3 ft, the maximum in 1955 was 3.2 ft on January 6th (actual ranges of tropic tides are shown in Table 2). Equatorial tides may have a range of only 0.5 ft and average 1.0 ft. The range of the daily tides increases towards the solstices, when the sun's daily component is greatest, and decreases towards the equinoxes (Table 1); the range of equatorial tides varies little through the year.

The range of the tide is also influenced to a lesser extent by the synodic and anomalistic cycles, so that the greatest tidal ranges are normally recorded when the moon is *at the same time:* (a) new or full (maximum synodic influence), (b) at perigee (maximum anomalistic influence), and (c) at maximum declination N. or S. (maximum tropic influence). Conversely, minimum ranges occur when the moon is at the same time (a) in its first or last quarter, (b) at apogee, and (c) above the equator. The reason for this will be clear from the statements on the causes of the tides.

The effect of these forces on the Fremantle tides does not appear to have been fully understood by earlier writers. Curlewis (1915) says: "Contrary to what might be expected the highest tide and greatest range happens when the moon is at its farthest North point, and not at its greatest South declination, when the moon would be almost directly over Fremantle, and would thus be in a position to exercise the maximum attractive force on the water." On the other hand, Bennett (1939) gives a graph which shows that the range of the tide is about 0.4 ft greater when the moon is at greatest declination south than when it is at greatest declination north.

The cause of this discrepancy lies in the fact that each author based his conclusion on the examination of the records for a single year. As stated above, the anomalistic month is 27½ days and the tropic month 27⅓ days. Consequently, throughout certain years, when the moon is at its greatest north declination it is also near perigee, and when it is at its greatest

TABLE I

Mean Monthly Range of Tide in Feet

Tropic lunar months	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	Means
Tropic Tides (means for 5-day periods)														
Geraldton, 1928–30	2·7	2·4	2·0	1·8	2·0	2·4	2·5	2·4	2·2	1·8	1·9	2·3	2·7	2·2
Fremantle, 1953–55	2·2	1·9	1·7	1·9	2·0	2·3	2·1	1·9	1·4	1·4	1·7	2·2	2·3	1·9
Albany, 1953–55	3·0	2·6	2·2	2·2	2·5	2·8	2·8	2·7	2·3	2·2	2·5	2·7	3·1	2·6
Equatorial Tides (means for 3-day periods)														
Geraldton	1·3	1·3	1·3	1·2	1·1	1·1	1·1	1·1	1·1	1·3	1·3	1·2	1·2	1·2
Fremantle	1·1	1·0	1·0	1·1	1·0	0·9	0·9	0·9	1·0	1·0	1·0	1·0	1·0	1·0
Albany	1·2	1·5	1·8	1·7	1·8	1·1	1·0	1·5	1·6	1·8	1·6	1·8	1·1	1·5

TABLE II

Range of tides at Fremantle.

Five-day periods about greatest lunar declination, when the moon is also at apogee or perigee. Figures show date, and range of tide in feet.

Declination of Moon	Moon at Apogee				Moon at Perigee			
	January	April	June	August	January	April	June	August
		1951				1955		
	(18) 1·6	(10) 1·6	(4) 2·0	(24) 1·2	(4) 2·0	(23) 2·1	(17) 1·8	(12) 2·3
	(19) 1·9	(11) 1·8	(5) 2·2	(25) 1·4	(5) 2·6	(24) 2·2	(18) 2·4	(13) 2·4
NORTH	(20) 2·0	(12) 1·8	(6) 1·9	(26) 1·2	(6) 3·2	(25) 2·1	(19) 2·9	(14) 2·8
	(21) 2·2	(13) 1·6	(7) 1·6	(27) 1·3	(7) 2·7	(26) 2·0	(20) 3·0	(15) 2·4
	(22) 2·0	(14) 1·7	(8) 1·7	(28) 1·6	(8) 2·7	(27) 1·8	(21) 2·6	(16) 2·0
Mean	1·9	1·7	1·9	1·3	2·6	2·0	2·5	2·4
		1955				1951		
	(18) 1·9	(10) 1·6	(4) 1·8	(24) 1·9	(5) 2·7	(23) 2·2	(17) 2·2	(11) 1·5
	(19) 1·8	(11) 1·5	(5) 1·7	(25) 1·1	(6) 2·7	(24) 1·9	(18) 2·5	(12) 2·0
SOUTH	(20) 2·2	(12) 1·5	(6) 1·9	(26) 1·2	(7) 2·9	(25) 2·4	(19) 3·2	(13) 2·3
	(21) 2·0	(13) 1·5	(7) 1·8	(27) 1·1	(8) 2·9	(26) 2·6	(20) 2·5	(14) 2·4
	(22) 2·3	(14) 1·4	(8) 1·6	(28) 2·0	(9) 2·4	(27) 2·4	(21) 2·6	(15) 2·7
Mean	2·0	1·5	1·8	1 5	2·7	2·3	2·6	2·2

Means: Moon at apogee .... 1.7 ft. Moon's declination north 2.05 ft. 1951 2.1 ft.
Moon at perigee .... 2.4 ft. Moon's declination south 2.15 ft. 1955 2.0 ft.

south declination it is also near apogee; after 4 to 5 years the opposite combinations occur. 1951 and 1955 were two such years. In Table 2 are shown the tidal ranges for the 5 days closest to greatest declination north and south in January, April, June, and August of these years. At these times the moon was also near the full or new. From this table it is clear that the tidal range was significantly greater when the moon was at perigee (2.4 ft) than at apogee (1.7 ft) irrespective of whether the moon was north or south of the equator.

Sea Level: Meteorological and hydrological factors.—While the maximum tidal range in any 24-hour period is only 3 ft, the extreme range from highest high water to lowest low water recorded over half a century is about 6 ft. The discrepancy between these two ranges is caused by the influence of meteorological and hydrological forces which produce changes in sea level of the same order of magnitude as the astronomic tides.

Offshore winds (those having an easterly component) tend to lower the water level, while onshore winds (with a westerly component) tend to raise the level of the water. The influence of the wind varies both with its strength and the angle at which it strikes the coast. The winds also affect the time of high and low water (see below).

High barometric pressure tends to lower sea level and low pressure to raise it. Bennett (1939) states that a rise of 1 inch in pressure causes a fall of 1.37 ft in water level. This figure appears to have been determined empirically for 1933 and differs from the theoretical value of 1.13 ft. It is in any case only an approximation since sea level is influenced not only by pressure at the place of observation, but by that over a considerable area of ocean.

The effect of weather conditions on sea level may be illustrated by the examples in Fig. 3. On May 26th and 27th, 1955, an extensive winter-type cyclone brought continuous westerly winds with a velocity of 25 to 30 knots which replaced the easterly winds of 24th, and the barometer fell from 30.2 in. to 29.4 in.; as a result sea level rose 2.1 ft from 2.6 ft (the mean value for the year) on 24th to 4.7 ft on 26th. The approach of the tropical cyclone of March 1956 caused a progressive rise in sea level from 2.0 ft above datum on 2nd to 3.3 ft on 4th. Both records show many minor oscillations, with a range (on this gauge) of up to about 0.3 ft and with a period of from about 15 minutes to an hour. These oscillations have various causes and may result from disturbances near the site of the gauge or at a distance of thousands of miles. The reason for the very low tides of December 1947 is not evident; the astronomical forces combined to produce maximum range tides (on 29th), but the winds and pressures recorded would not be expected to cause an abnormally low sea level. Variation in daily sea level is also evident in the two records reproduced in Figs. 1 and 2.

Figure 4 shows a marked seasonal shift in sea level, which tends to be about one foot higher in winter than in summer. The irregularity in the record and the marked differences from one year to another are however evident. Bennett (1939) ascribed this shift to the solar annual tide wave (Sa) and went on to say that, "it was directly proportional to the declination of the sun," the influence of which is semiannual. Neither the annual (Sa) nor the semiannual (Ssa) constituents of the tide are attributable to the very small astronomical forces with these periods. Curlewis (1915) says that, "the exceptional height often reached by the tides during the winter months is almost solely due to the banking up of the water against our western

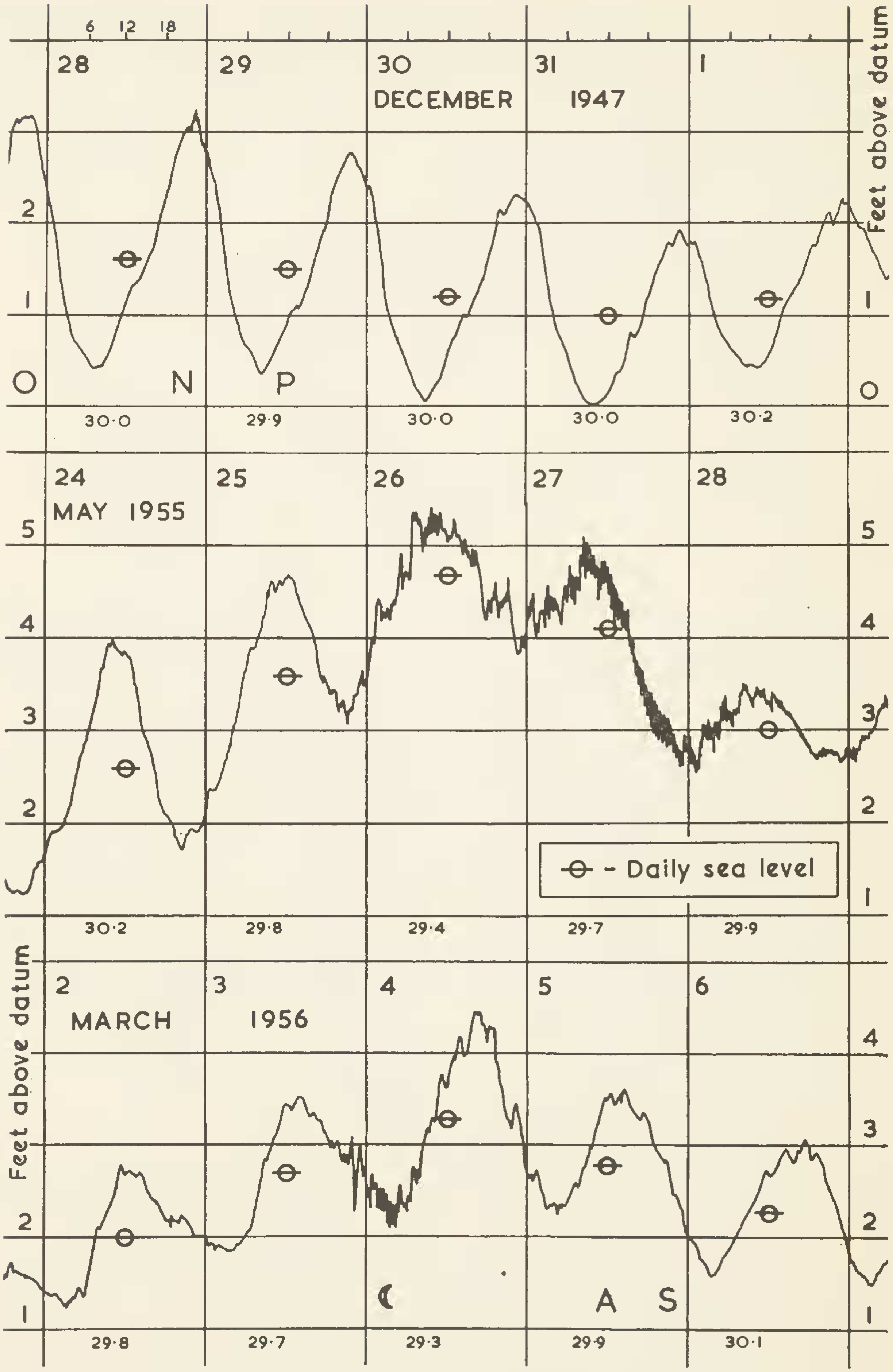

Fig. 3.—Fremantle tide record, to show influence of weather on sea level. Figures show barometric pressure in inches at 0900 hours. For symbols see Fig. 1.

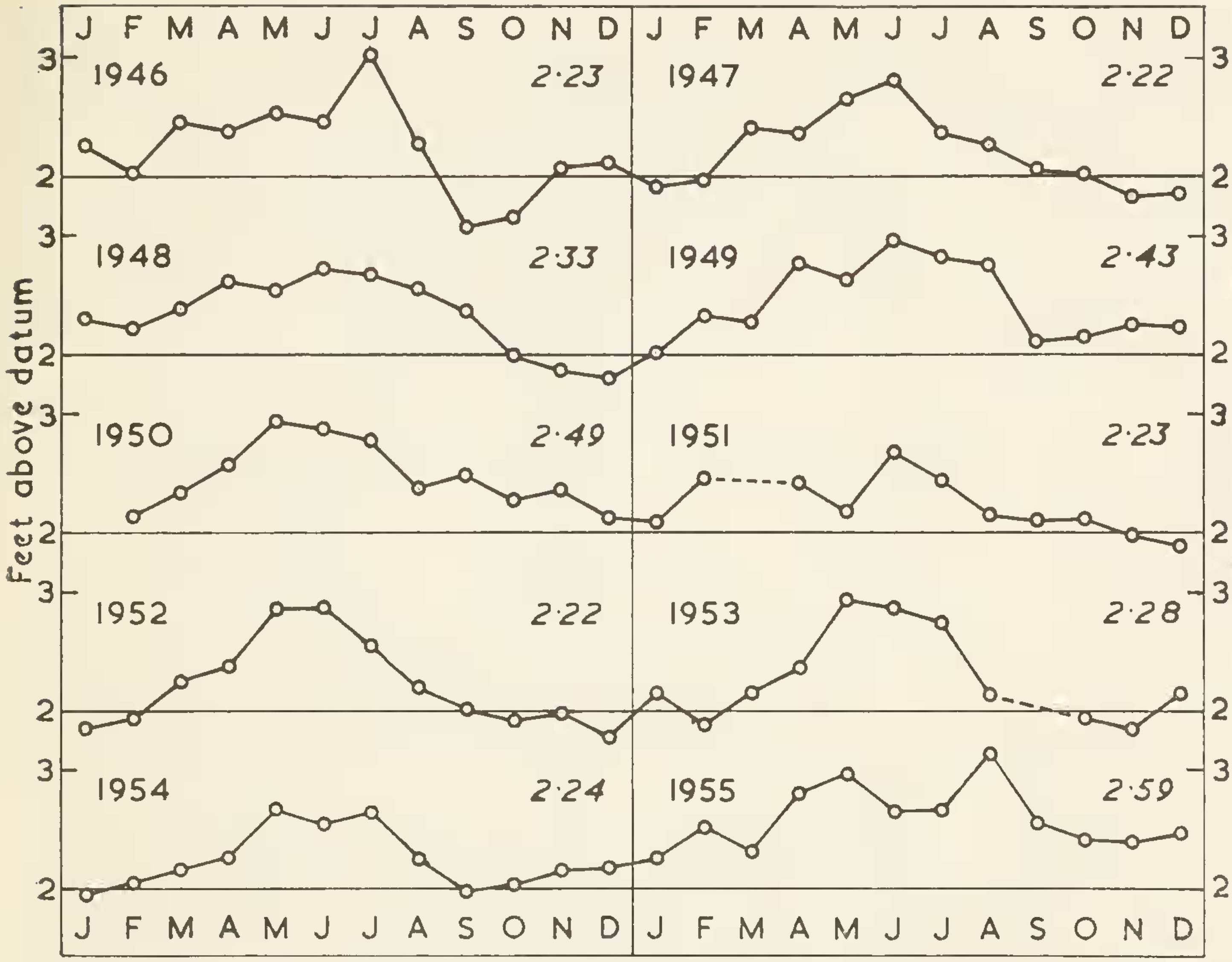

Fig. 4.—Monthly sea level at Fremantle, 1946-1955. Planimeter measurements by P.W.D., Perth.

coast line" by the westerly winds. Prevailing onshore winds tend to raise the sea level in winter and offshore winds to lower it in summer (Marmer, 1926). Mean barometric pressure varies little, but tends to be lower in summer than in winter so that this would cause the reverse effect to that observed.

Patullo *et al* (1955) attribute the shift mainly to changes in steric sea level, caused by water temperature and salinity at all depths (mainly temperature in these latitudes). Surface water temperatures are out of phase with the changes in level, maximum temperatures generally occur in March-April and minimum temperatures in September-October; however the scanty records available of water temperatures at 200 metres show the lowest figures in midsummer and the highest in midwinter (Rochford 1951 and 1953).

The seasonal shift must be presumed to be the resultant of the effects produced by these various forces, principally water temperature and prevailing winds.

Because of this fluctuation in sea level, the proportion of the time that any point in the intertidal belt is out of the water, or submerged, varies greatly through the year. Curves of percentage exposure for January and May 1954 are shown in Fig. 5; these were the months with lowest (1.94 ft) and highest (2.66 ft) monthly sea level. The extreme monthly levels during the ten-year period 1946-1955 were 3.13 ft (Aug. 1955) and 1.57 ft (Sept. 1946). Over shorter periods the range of level is of course much greater and daily sea level may lie anywhere between 5 ft and 1 ft above datum, when the curves are correspondingly higher or lower.

Mean sea level was calculated by N. J. Henry (MS. in Public Works Department, Perth) to be 2.480 ft above datum; the figure was later confirmed by the Liverpool Observatory and Tidal Institute. However it will be seen from Fig. 4 that even the annual M.S.L. is not constant from year to year, and in this ten-year period varies from 2.22 ft to 2.59 ft with a mean of 2.33 ft. The cause of these changes is not evident, they are presumably attributable to a combination of the meteorological and hydrological factors mentioned above.

Times of the tides.—From December to early April and from June to August the time of L.W. remains constant within two or three hours throughout each half tropic cycle (from one zero declination to the next). During the inter-

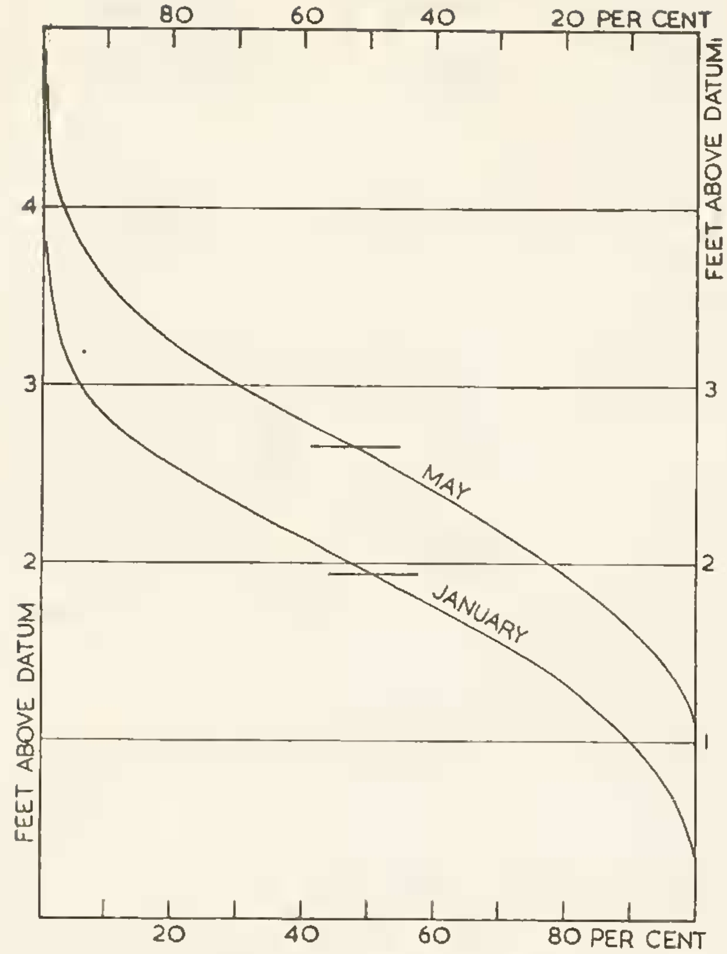

Fig. 5.—Percentage of time submerged or exposed at heights above datum. Fremantle, January and May, 1954.

vening months L.W. tends to show the more usual progression of 50 minutes later each day. The time of H.W. averages about 50 minutes a day later through each half cycle, but there is much variability and in some months it does not move more than 4 hours during a half cycle. Both H.W. and L.W. become earlier through the year. The predicted times of the tides in 1955 are shown in Fig. 6; they differ little from year to year. It will be seen that L.W. is in the early morning in summer and in the late afternoon in winter.

When equatorial tides are of semidaily type H.W. and L.W. succeed one another at six-hour intervals, while at tropic tides they are approximately 12 hours apart. From one series of tropic tides to the next the intervals between successive lows and highs may be almost anything from 6 to 18 hours (Fig. 1). From Fig. 1 it will also be noted that as one peak wanes at the equatorial tides a second waxes and replaces it.

The time of high and low water may be delayed or advanced up to two hours by strong winds. The time of H.W. is advanced by westerly winds and retarded by easterly winds; the time of L.W. is retarded by westerly winds and advanced by easterly winds, as compared with predictions.

The statements of Bennett (1939) with regard to the times of high and low water require modification, and predictions derived from his Fig. 6 are often up to 5 hours out.

Summary.—The tides at Fremantle vary with the tropic lunar cycle, which has a period of $27\frac{1}{3}$ days. When the moon is at its greatest declination N. or S. the tides are of daily type and have a maximum range of about 3 ft. at the solstices and $2\frac{1}{2}$ ft at the equinoxes (means for 3 years: 2.3 ft and 1.5 ft respectively). When the moon is near zero declination the tides have a mean range of 1.0 ft and a minimum of 0.5 ft; near the equinoxes these equatorial tides are of semidaily type for about five consecutive days, but near the solstices they are of daily type (often with one H.W. or L.W. and a prolonged period when the tide stands near the other extreme).

This pattern alters little with the changing phases of the moon, spring tides increase the range of the tides slightly and neap tides decrease them. Similarly the range is greater when the moon is at perigee than at apogee.

Superimposed on this regular predictable cycle are changes in sea level caused by variation in barometric pressure, in the strength and direction of the winds, and the temperature and salinity of the water. These may combine to cause a variation in daily sea level of about 4 ft, which is thus of the same order of magnitude as the small tidal range. Mean (monthly) sea level is nearly one foot higher in winter than in summer, but there is great variation from year to year.

The times of H.W. and L.W. are predictable; but they may be delayed or advanced by up to a couple of hours by the winds. During most of the year L.W. recurs daily at about the same time throughout any one lunar cycle, being in the early morning in summer and in the late afternoon in winter.

Geraldton.

An automatic recording gauge was operated here for about 15 years to 1930. The records for 1926 to 1930 have been studied.

The tides closely resemble those at Fremantle, being mainly of daily type, but with tides of semidaily type when the moon is near zero declination. Semidaily tides occur on from 10 to 12 days in each calendar month at the equinoxes, and from none to 1 or 2 near the solstices. The maximum tidal range at Geraldton is greater than at Fremantle, and tides of 3.6 ft range were recorded in January and June 1930. Equatorial tides also have a slightly greater range than at Fremantle and the minimum recorded in 1930 was 0.7 ft. Mean monthly ranges are shown in Table 1.

The datum now accepted for the port is 1.5 ft. below zero on the existing gauge. Monthly sea levels are shown in Table 3 and it will be seen that here, as at Fremantle, there is a seasonal shift with higher levels in winter and lower in summer.

Times of H.W. and L.W. at Geraldton are generally between 2 and 3 hours earlier than at Fremantle.

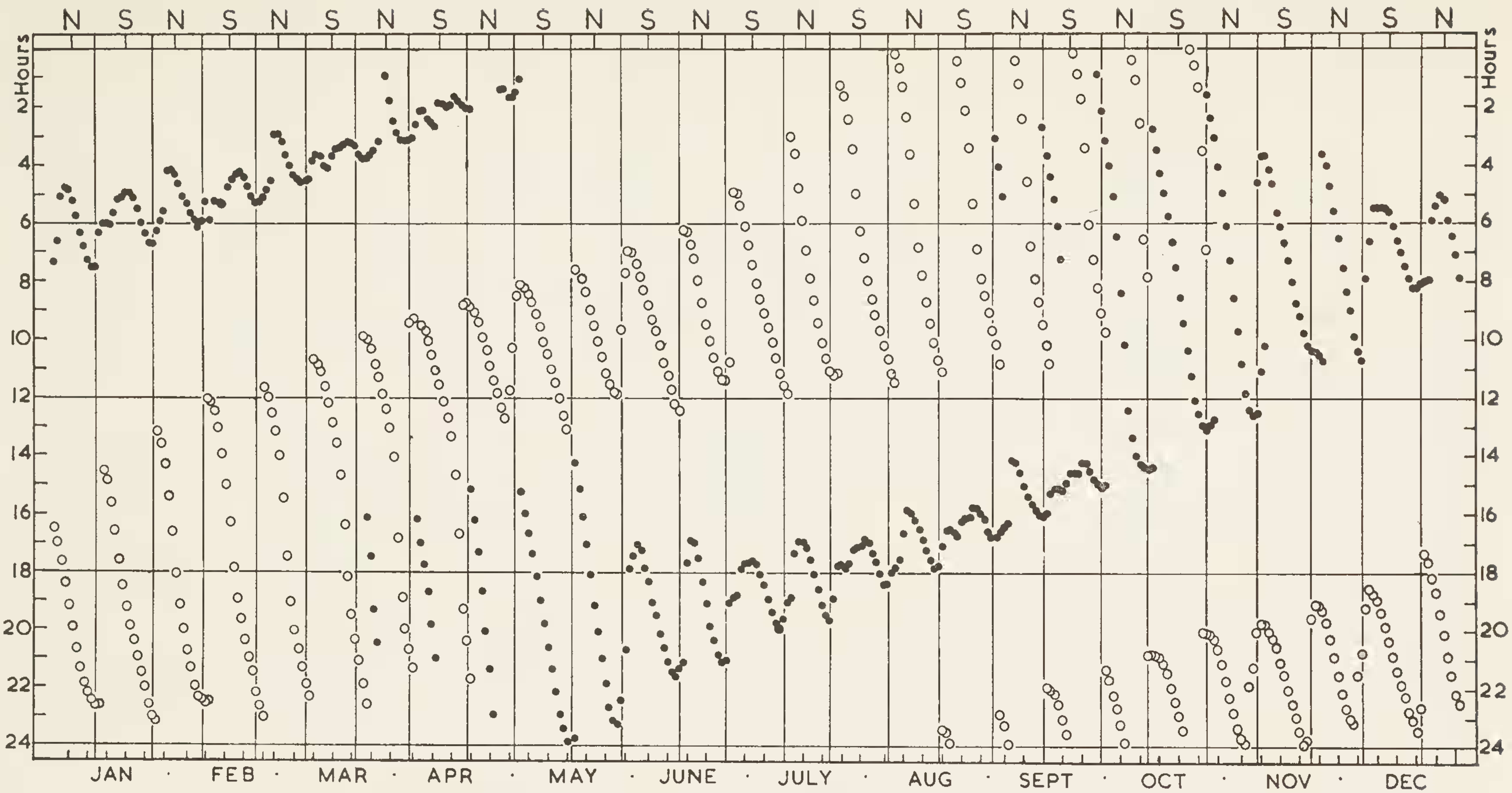

Fig. 6.—Predicted time of principal tide at Fremantle, 1955. Solid circles—Low water. Open circles—High water. Vertical lines—zero declination.

TABLE III

Monthly sea level, feet above datum (planimeter measurements)

	J.	F.	M.	A.	M.	J.	J.	A.	S.	O.	N.	D.	Mean
Geraldton, 1930	2·43	2·42	3·12	3·18	3·33	3·63	3·22	3·10	2·95	2·78	2·62	2·89	2·97
Fremantle, 1955	2·26	2·51	2·31	2·80	2·97	2·64	2·67	3·13	2·56	2·41	2·40	2·46	2·59
Albany, 1955	1·98	1·96	2·55	2·58	2·70	2·80	2·71	2·06	2·12	2·33	2·12	2·10	2·33

Bunbury.

An automatic recording gauge has been operated here since 1930. The 1955 record was compared with the Fremantle record for the same year; the two are very similar throughout. The daily range at Bunbury is only slightly greater than at Fremantle, but the extreme range is about 1 ft more.

The datum now accepted is 1.0 ft above zero on the gauge.

The times of H.W. and L.W. are up to about 1 hr later than at Fremantle.

Albany.

An automatic recording gauge has been operated here since 1952. The 1954 and 1955 records were studied and compared with the Fremantle records.

The tides at Albany have the same general character as those at Fremantle. Tides of semi-daily type are slightly more frequent, and near the equinoxes they last for 14 to 16 days in a calendar month.

The range of tropic tides is always greater than at Fremantle (about 0.7 ft); equatorial tides are of similar range to those at Fremantle at the solstices but 0.8 ft. greater at the equinoxes. The maximum range in 1955 was 3.9 ft on Dec. 28, the minimum 0.9 ft on June 14. Mean monthly ranges are shown in Table 1.

The setting of the zero on the gauge at Albany is accepted as true datum for the port. The seasonal shift in sea level shown by the monthly means given in Table 3 is of the same type as at Fremantle. The difference between highest and lowest monthly M.S.L. in 1955 was 0.84 ft.

Times of H.W. and L.W. at Albany may be up to about 2 hours later than at Fremantle. There is the same shift in the times of H.W. and L.W. through the year.

Tides on the North-West Coast

Although outside the scope of the present paper, a brief statement on the tides on the coast of Western Australia north of Geraldton is not out of place as it serves to emphasise the difference between the tides of the south-west and the tides of more usual type which occur on our northern coastline.

The available information is scanty and some of it is unreliable or open to misinterpretation. The best general sources are Chapman (1938) and the tide tables issued annually for Port Hedland. The following are the mean spring ranges given by Chapman.

Port Darwin	24 ft.
Wyndham	23 ft.
Collier Bay	36 ft.
Derby	34 ft.
Broome	28 ft.
Port Hedland	19 ft.
Cossack (Roebourne)	18 ft.
Fortescue	13½ ft.
Maud Landing	6 ft.
Carnarvon	5 ft.

These are substantially the same as the "spring rise" given in the tide tables because, datum is at about lowest low water. It should be noted that the figures for "neap rise" in the tables are also heights above datum and only a rough approximation to neap range can be gained from them. We are informed by Capt. G. D. Tancred, R.A.N., Senior Officer, Hydrographic Service, that the figure for spring range at Darwin should be 18 ft and that for Wyndham 24 ft.

It will be observed that from Roebourne northwards the tidal range is great, but that south of this port the range decreases rapidly.

Tide predictions are published for Port Hedland, where a recording tide gauge has been operated since 1913. The tides are of semi-daily type with a mean spring range of about 20 ft (1949: mean 20.7 ft, max. 24.1 ft, min. 17.2 ft) and a neap range in 24 hours of between 3 ft and 7 ft. Spring and neap tides follow from 1 to 3 days after the appropriate phases of the moon (data from tide tables). An account of the Port Hedland tides is given by Curlewis (1915).

At Onslow the tides are of similar type to those at Port Hedland, but the spring range is only 8½ ft, and neap range 1½ ft. Both height and time of tide may be considerably modified by weather conditions (information from Mr. A. H. Clark, Warfinger, Onslow). Predictions for Learmonth (courtesy of West Australian Petroleum Pty. Ltd.) show tides of similar type and range; spring range averages 8 ft (1956: max. 8.6 ft, min. 7.0 ft) and neap range between 2 ft and 4½ ft. There is considerable diurnal inequality up to 2½ ft between the tides near maximum lunar declination.

At Carnarvon observations were made with a tide pole during daylight hours from November 1938 to November 1939. The tides are predominantly of semidaily type, but there are often tides of mixed type, and occasional tides of daily type from November to January. They follow closely the pattern of the Port Hedland tides, with the greatest range at spring tides a few days after full and new moon. However, the range is much smaller; spring range is about 4 ft, one fifth of that at Port Hedland, and neap range in 24 hours varies from 1 ft to 3 ft (mean 1.9 ft). Mean sea level varies considerably, presumably with atmospheric and hydrologic conditions, and in 1939 extreme H.W. was 6.0 ft and extreme L.W. 0.2 ft above datum. H.W. and L.W. are at about the same time as at Port Hedland (information from Public Works Department, Perth).

Conclusions

(i) On the coast of Western Australia, from north of Geraldton probably to the South Australian border, the tides are predominantly of daily type. Both type and range of tide change with the tropic (declinational) lunar cycle of 27⅓ days. "Tropic" tides, when the moon is near its greatest declination north or south, are always of daily type; while "equatorial" tides, when the moon is near zero declination, tend to be of semidaily type. The daily range of the tide is greatest near the tropic tides and least near equatorial tides (it is not correct to use the terms "spring" and "neap" for these maximum and minimum range tides).

The range of the tides is also influenced by the synodic and anomalistic lunar cycles; it tends to be greater at full and new moon than at first and last quarters, and at perigee than at apogee. These influences are however masked by the declinational effect.

(ii) Both type and range of tide also change with the sun's declination. Near the solstices there are few tides of semidaily type, none in December and June, while at the equinoxes they occur on from 10 to 16 days in each calendar month. Tropic tides have their greatest range near the solstices and least near the equinoxes; a maximum range of about 3.0 ft and 2.5 ft respectively at Fremantle.

(iii) Between the daily and semidaily tides near the equinoxes, and at equatorial tides near the solstices there are mixed tides intermediate in form between the daily and semidaily types. At these times, vanishing tides stand near high or low water for some hours, or at some intermediate level.

(iv) The type of the tides is essentially similar at all four ports studied (Geraldton, Fremantle, Bunbury, and Albany), except that the number of semidaily type tides is slightly greater at Albany than elsewhere, and that at this port equatorial tides are of greater range at the equinoxes than at the solstices. The range of both daily and semidaily type tides is least at Fremantle and increases north and south of this port.

(v) Changes in sea level caused by meteorological and hydrological forces are of the same order of magnitude as those caused by astronomical forces. At Fremantle daily sea level may lie anywhere between 1 ft and 5 ft above datum. Sea level is always higher in winter than in summer; the difference between the highest and lowest monthly means in any one year at Fremantle is about 1 ft. There is considerable variation from year to year.

Sea level varies inversely with the barometric pressure (though the relation is not a simple one) and directly with the temperature of the water. Offshore winds lower and onshore winds raise the sea level.

(vi) Low water of daily type tides is in the early morning in summer, and in the late afternoon in winter; the time only varies by about 2 hours in any half lunar cycle, but gets earlier through the year. The change from morning to evening tides takes place in April-May and from evening to morning in September-November, and in these months the time of L.W. moves through about 8 hours during each half cycle. The time of H.W. is much less constant and ranges from about 6 hours after L.W. to about 6 hours before L.W.

Tides are about 2 hours earlier at Geraldton than at Fremantle and up to about 2 hours later at Albany. Offshore winds may delay and onshore winds advance the time of H.W. as much as two hours; similarly onshore winds delay and offshore winds advance the time of L.W.

(vii) Along the north-west coast from Shark Bay to Wyndham the tides have a very different character. They are semidaily, and of the synodic or phase type characteristic of north Atlantic coasts; spring and neap tides alternate over the 29½ day synodic cycle.

From Roebourne northwards the tidal range is great (over 18 ft at springs), but from Onslow (8½ ft) southwards it decreases progressively and at Carnarvon the spring range is no greater than the range of tropic tides at Geraldton.

Proceeding southwards also, the daily component of the tides increases; at Carnarvon successive tides may be of very unequal height and occasional tides of daily type occur at maximum lunar declination near the solstices.

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